Chirped multilayer coatings for broadband dispersion control in femtosecond lasers

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Optical thin-film structures exhibiting high reflectivity and a nearly constant negative group-delay dispersion over frequency ranges as broad as 80 THz are presented. This attractive combination makes these coatings well suited for intracavity dispersion control in broadband femtosecond solid-state lasers. We address design issues and the principle of operation of these novel devices.

The relevance of intracavity dispersion control in passively mode-locked ultrashort-pulse laser was recognized soon after the appearance of the first systems operating in the femtosecond domain.[1] Negative dispersion that is due to wavelength-dependent refraction in a pair of Brewster-angled prisms combined with positive material dispersion proved to be an efficient and convenient means of controlling the net group-delay dispersion (GDD) inside the laser cavity.[2]

In solid-state lasers femtosecond pulse generation invariably relies on a net negative intracavity GDD because of an ultrafast self-phase modulation caused by the optical Kerr effect in the laser medium. Hence prism pairs have become standard components in these systems. The interplay between negative GDD and Kerr-induced self-phase modulation, often referred to as solitonlike shaping, appears to be the dominant pulse-forming mechanism that determines the steady-state pulse duration in femtosecond solid-state lasers.[3] In practical prism-pair-controlled broadband laser systems a major limitation to ultrashort pulse generation originates from the variation of the intracavity GDD with wavelength. The principal source of this high-order dispersion was found to be the prism pair.[3,4] In this Letter we report the novel development of chirped multilayer mirror coatings that can exhibit essentially constant negative GDD over a frequency range as broad as 80 THz. Careful design permits higher-order contributions to the mirror phase dispersion to be kept at low values or to be chosen such that high-order phase errors introduced by other cavity components (e.g., the gain medium) are canceled. Replacing the prism pair with these novel devices offers the potential of generating pulses that are shorter than previously achievable directly from the laser. In addition, this simplifies the cavity design and may permit the construction of more compact and reliable femtosecond sources.

The first thorough investigations of the frequency-dependent phase retardation (phase dispersion) of multilayer dielectric coatings date back to the early 1960's.[5,6] The emergence of femtosecond lasers in the 1980's has led to a revival of interest in this field.[7-13] Whereas standard quarter-wave dielectric mirrors were shown to introduce negligible dispersion at the center of their reflectivity bands,[7,8,11] various specific high-reflectivity coatings (Gires–Tournois interferometers, double-stack mirrors, etc.) with adjustable GDD (through angle tuning) were devised and used for the precise control of intracavity dispersion in femtosecond dye lasers.[14,15] However, the GDD introduced by these mirror coatings is accompanied by high cubic and higher-order dispersive contributions. As a consequence, a constant GDD could be obtained only over a limited wavelength range (<10 THz). The difficulty in realizing broadband GDD control relates to the physical origin of dispersion in these devices; different frequency components are trapped for different periods of time in Fabry–Perot-like resonant structures.

A distinctly different type of GDD arises from the wavelength dependence of the penetration depth of the incident optical field in multilayer coatings. This effect does not rely on the presence of resonant structures and offers the possibility of realizing a GDD that is a slowly varying function of wavelength over a broad bandwidth. A constant GDD requires a group delay that varies approximately linearly with the wavelength. A wave packet of a given center wavelength is most efficiently reflected by a corresponding quarter-wave stack. Therefore a monotonic variation of the multilayer period throughout the deposition process (chirped coating) should result in a penetration depth[16] (and thus group delay) that varies monotonically with the wavelength. However, a previous study of chirped multilayer coatings with layer thicknesses following monotonic variations revealed that the GDD is strongly perturbed by some Fabry–Perot-like resonances in these simple structures.[17] Our studies have indicated that the undesirable resonant features can be almost completely eliminated by

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